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QCD resummation for new variables to study dilepton transverse momentum

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in collaboration with A.Banfi, M.Dasgupta arXiv:1102.3594 [hep-ph]
and L. Tomlinson (work in progress)

Outline

- Motivation for studying the EW boson transverse momentum
- Novel variables
- Study of the ϕ^* distribution:
  - resummation to NNLL
  - matching to fixed order
- Comparison to D0 data (preliminary)
- Conclusions and Outlook

Transverse momentum

- The transverse momentum distribution of the lepton pair (or of the gauge boson) is very interesting
  - It is sensitive to multi-gluon emission from the initial state partons
  - The correct treatment of these effects goes beyond fixed order perturbation theory: we need resummation
- Very precise measurements together with accurate theoretical calculations can pin down the non-perturbative contribution (intrinsic transverse momentum of the initial state quarks)
- An accurate theoretical description of the transverse momentum of weak boson is important for the extraction of the W mass
- We want to improve and validate the theoretical tools using Tevatron data to be able to do accurate phenomenology at the LHC

Different scales

- Let us call
  - Q_T: transverse momentum of the Z boson
  - M: invariant mass of the lepton pair (close to the Z mass)

- In principle we have to consider three different regimes

$$Q_T \quad \sim \quad M$$

Fixed order PT works: NLO programs like MCFM

Campbell and Ellis

$$\Lambda_{QCD} \ll Q_T \ll M$$

PT works but large logs in M/Q_T: need for resummation

$$Q_T \quad \sim \quad \Lambda_{\rm QCD}$$

Non-perturbative domain

Resummation beyond LL

- Resummation is based on factorization properties
- In the eikonal (soft) limit it easy to see that matrix elements factorize
- Less trivial is to properly treat momentum conservation, which is essential to go beyond LL
- We can achieve full factorization in impact parameter space

$$\delta^{(2)}\left(\sum_{i=1}^{n} \underline{k}_{Ti} + \underline{Q}_T\right) = \frac{1}{(2\pi)^2}\int d^2\underline{b}\, e^{i\underline{b}\cdot\underline{Q}_T} \prod_{i=1}^{n} e^{i\underline{b}\cdot\underline{k}_{Ti}}$$

- One of the problems with this approach in then the inversion back to momentum space (more later)

- Different sources of suppression: Sudakov and kinematic cancellation

Q_T -resummation

- In the usual transverse momentum resummation one is interested in the magnitude Q_T
- Hence one integrates over the angle between *b* and Q_T
- This results into a Bessel function J_0

$$\frac{d\sigma}{dQ_T^2} \simeq \int_0^\infty db\, b\, J_0(bQ_T) e^{-R(b)} \Sigma(x_1, x_2, \cos\theta^*, bM)$$

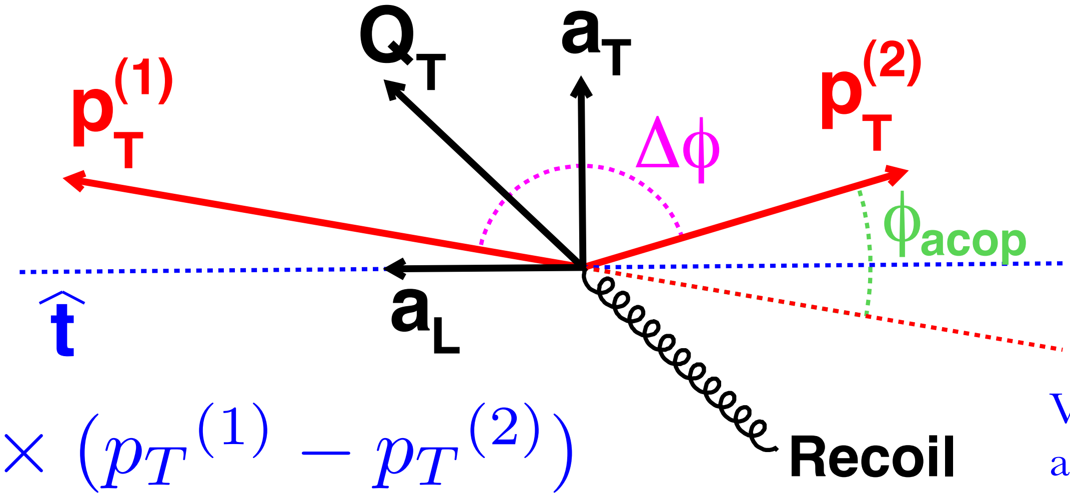
The radiator R contains all large logarithmic contributions

Σ contains the non-logarithmic terms convoluted with the PDFs

- The resummation of the Q_T spectrum has been widely studied
- Different groups, different formalisms (e.g. Collins, Soper, Sterman, Catani *et al.*)
- It is known to NNLL accuracy

New variables

- New variables introduced by the D0 collaboration for studying the transverse momentum of the Z boson
- From an experimental point of view one wants to measure angles rather than momenta



$$\underline{a}_T = \frac{\underline{Q}_T \times (\underline{p_T}^{(1)} - \underline{p_T}^{(2)})}{|\underline{p_T}^{(1)} - \underline{p_T}^{(2)}|}$$

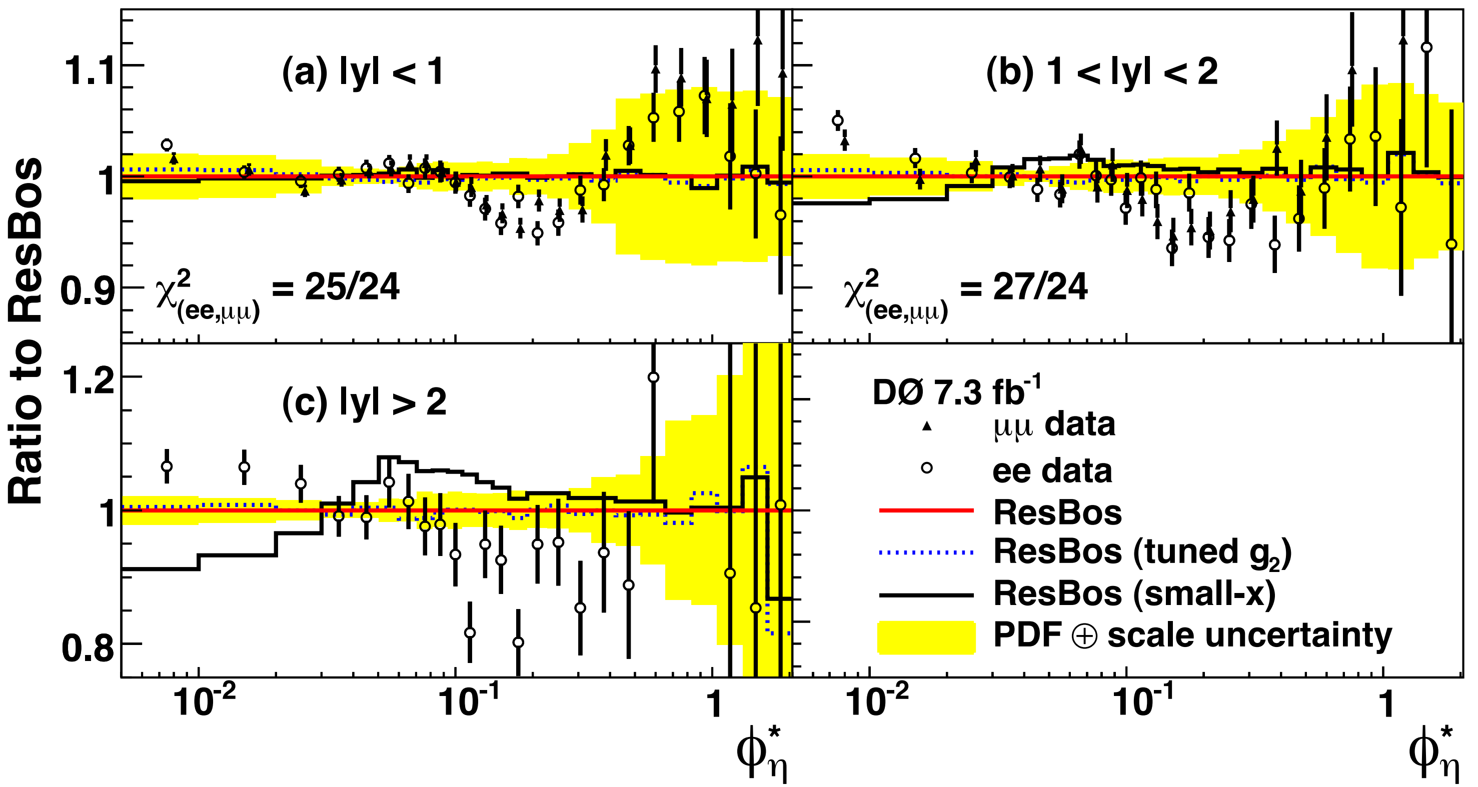
Vesterinen and Wyatt (*et al.*)
arXiv:0807.4956 [hep-ex]
arXiv:1009.1580 [hep-ex]

scattering angle in the frame where the leptons are aligned

$$\phi^* = \tan\left(\phi_{acop}/2\right)\sin\theta^*$$

it only depends on their pseudorapidities

D0 results



D0 collaboration
arXiv:1010.0262

- D0 compared their results with the program ResBos
- It resums the relevant logs at (N?)NLL (CSS formalism)
- It is matched to fixed order at NLO (for Q_T ?)
- Non-perturbative effects are controlled by a tunable parameter g_2
- Small-*x* smearing is disfavoured by data
- The theoretical understanding is not satisfactory: need of a precise study

Theory viewpoint

- From theory point of view: can we use the very well established Q_T resummation to study these new variables ?

- The a_T variable and its connection to Q_T already studied

Banfi, Duran and Dasgupta
arXiv:0909.5327

- The resummation for a_T is closely related to the one for Q_T

- Moreover, in the soft limit

$$\phi^* \sim \frac{a_T}{M}\,, \qquad Q_T \to 0$$

- So we can adapt the Q_T formalism to study ϕ^* as well

Resummation for ϕ^*

- In the case of these new variables we are interested in one of the components of Q_T rather than its magnitude
- In the b-space formalism this produces a cosine function rather than the Bessel function J_0 we have encountered before

the radiator resums large logs

$$\frac{d\sigma}{d\phi^*} = \frac{\pi\alpha^2}{sN_c}\int_0^\infty d(bM)\cos(bM\phi^*)e^{-R(b)}$$
$$\times\Sigma(x_1, x_2, \cos\theta^*, bM)$$

hard matrix elements and PDFs

- This has important phenomenological consequences
- In the case of these new variables the kinematical cancellation is the dominant suppression mechanism and it prevents the formation of a Sudakov peak

The radiator

- Let's have a closer look at the radiator

$$R(\bar{b}) = L g_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \ldots$$

$$L = \ln(\bar{b} M)$$

- The NNLL contribution known for some times Catani *et al.*
- However a piece of this result has been recently questioned

Becher and Neubert
arXiv:1007.4005

- We exponentiate only the NNLL contributions which are relevant at NLO
- In this way we will be able to control all the logarithmic terms at NLO which eases the matching procedure

Issues with the *b*-integral

- In order to obtain the final result we have to invert the Fourier integral
- It is well known that this integral is ill-defined both at small- and large- b

- Large-b: non pertubative region, Landau pole

$$g_1 = -\frac{C_F}{\pi\beta_0}\left[1 + \frac{\ln(1-\alpha_s\beta_0 L)}{\alpha_s\beta_0 L}\right]$$

$$L = \ln(\bar{b}M)$$

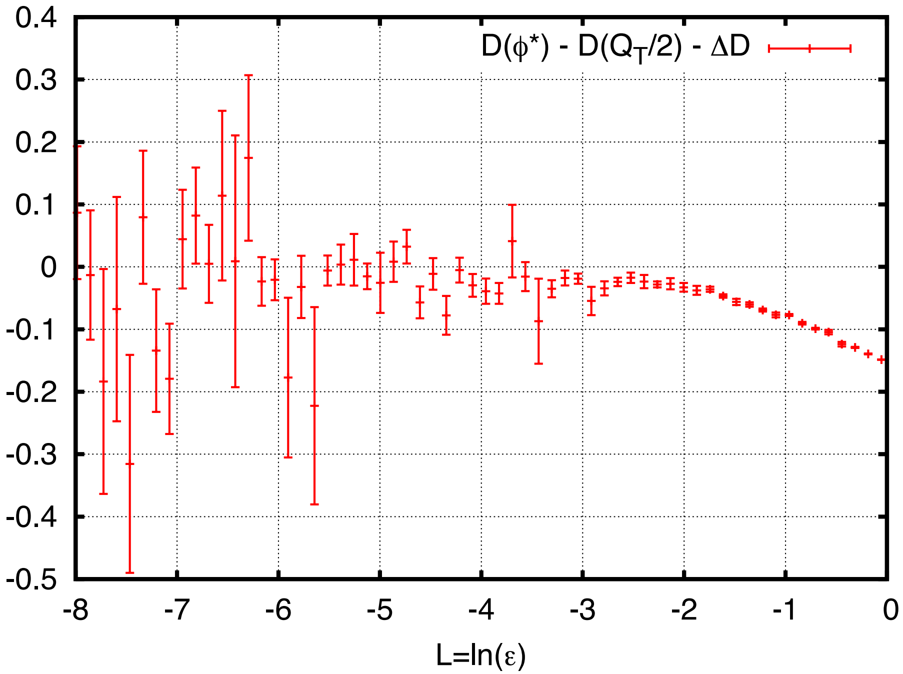
- We cut off the integration above a given b_{max}

- Small-b: spurious singularity outside the resummation region
- We freeze the radiator below a given b_{min}

- These are arbitrary prescriptions: they contribute to the theoretical uncertainty

Checking the logs

- Before presenting our final result for the resummed and matched distributions we have to check the logs
- We expand our resummation to second order and compare it to the fixed order result from MCFM Campbell and Ellis
- To test our understanding of the relation between ϕ^* and Q_T, we plot the difference of these distributions

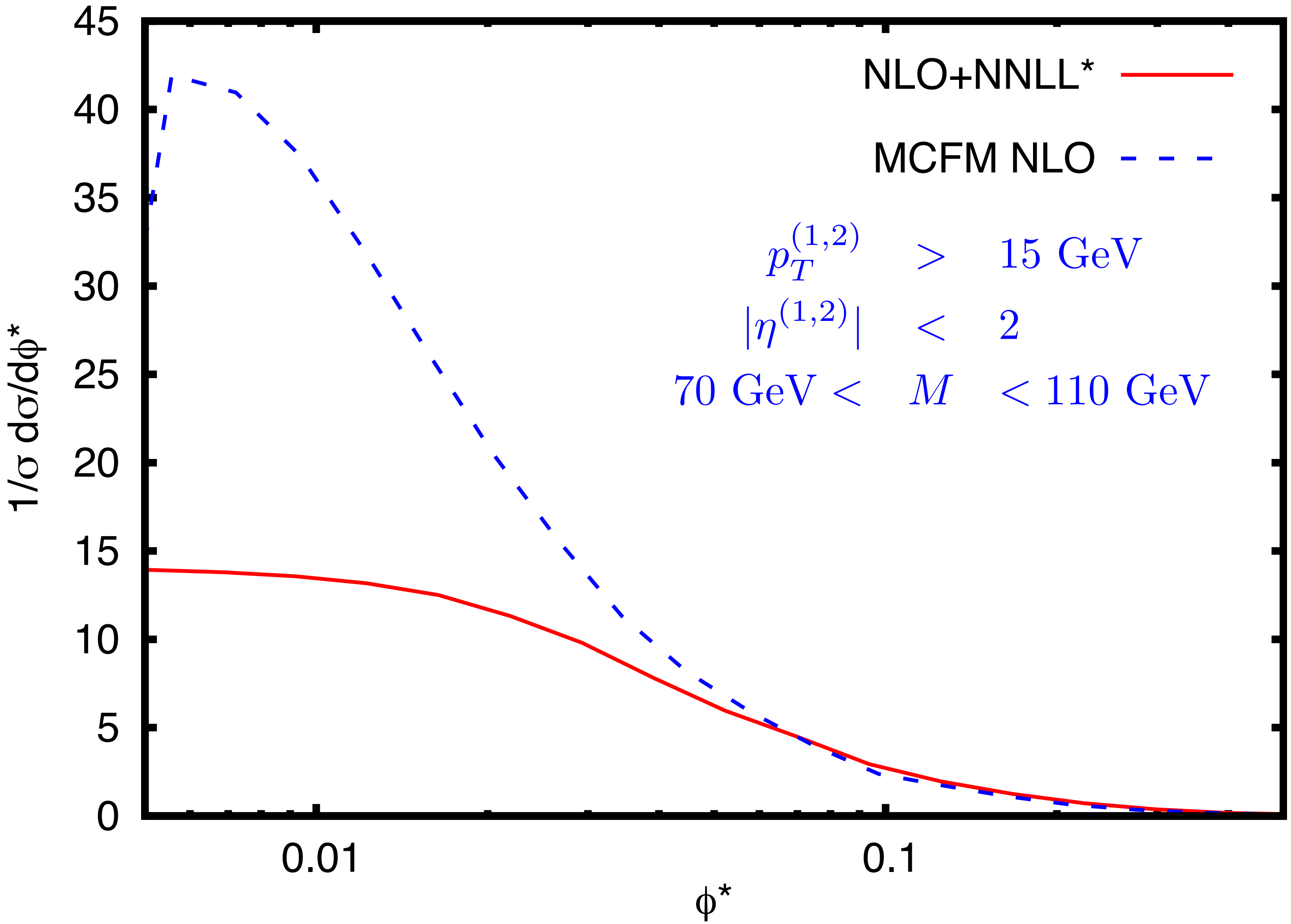


The difference between the expansion of the resummation and the NLO curve vanishes at large |L|

We have full control of next-to next-to leading logarithms at this order !

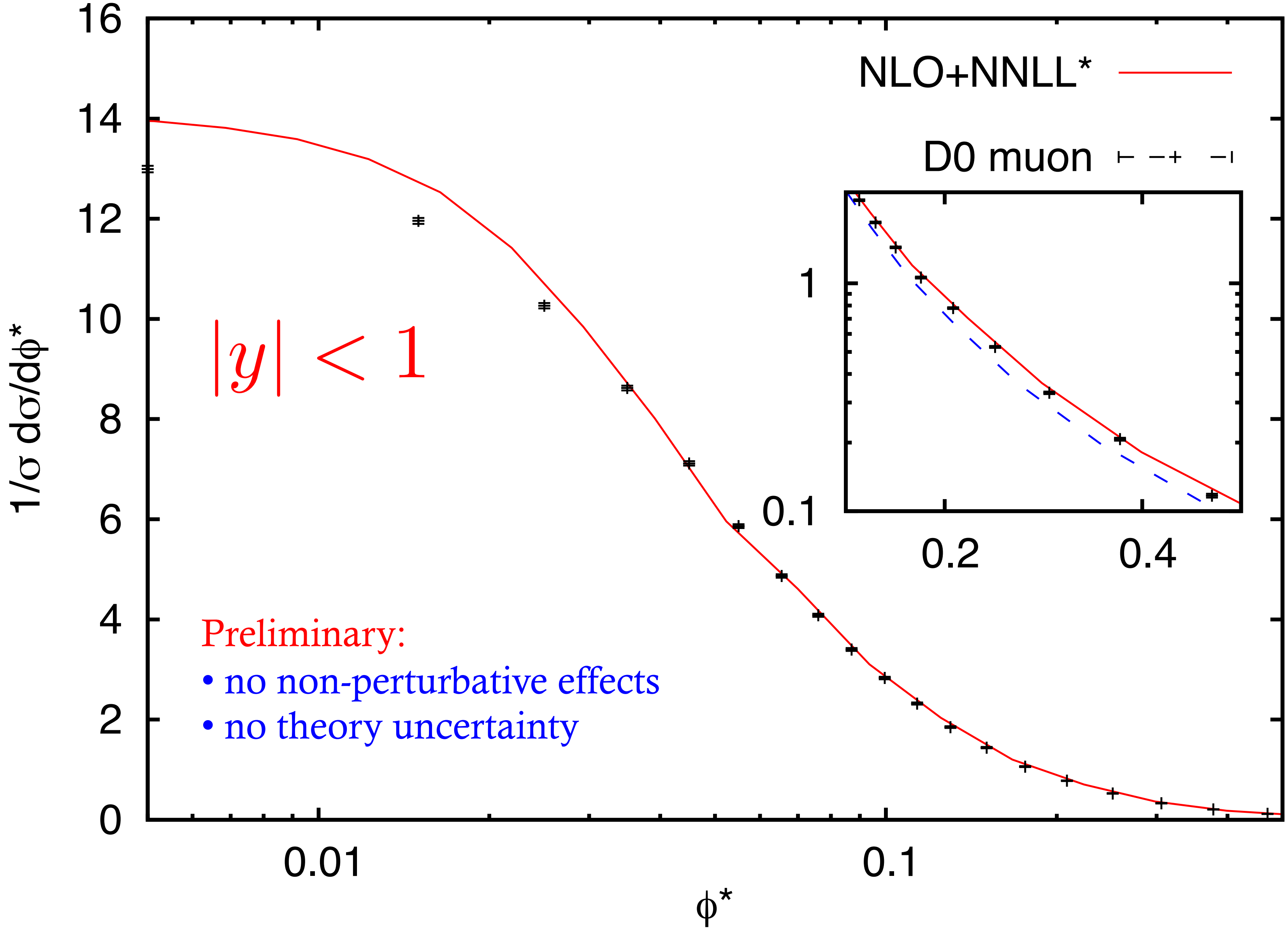
The matched result

$$\left(\frac{d\sigma}{d\phi^*}\right)_{\text{matched}} = \left(\frac{d\sigma}{d\phi^*}\right)_{\text{resummed}} + \left(\frac{d\sigma}{d\phi^*}\right)_{\text{MCFM}} - \left(\frac{d\sigma}{d\phi^*}\right)_{\text{expanded}}$$



- Smooth matching procedure: no need to switch off terms
- The matched curve and fixed order agree at large ϕ^*
- But they very much differ in a large region

Comparison to data



Conclusions

- The D0 collaboration has recently introduced novel variables to probe the Q_T spectrum of the Z boson
- The data are very accurate and disfavour non-pertubative models currently on the market
- We have started a dedicated study of the ϕ^* variable
- We want to compute the most accurate perturbative prediction in order to be able to extract non-perturbative effects
- Our theoretical calculation includes partial NNLL resummation matched to NLO calculation from MCFM
- Our matching procedure is particularly smooth
- Our preliminary results are very close to the D0 data (less than 8 % discrepancy in the last ϕ^* bin)

Outlook

- We need to implement full NNLL
- We have to estimate the theoretical uncertainty:
  - missing higher orders in the fixed-order part (estimating by varying renormalization and factorization scales)
  - missing higher orders in the resummation (estimating by varying the argument of the logs we resum)
  - different procedures to regularize the *b*-integral (cut-off, minimal prescription etc.)
- Having done that we will be able to properly compare to the D0 data and pin down the non-perturbative contribution